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Xing, Huili (Grace) and Jena, Debdeep

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275 Fitzpatrick Hall
Electrical Enginering Department
University of Notre Dame, Notre Dame, IN 46556

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Maki, Paul
Electronics, Sensors and Network Research (Code 312)
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14. ABSTRACT
AlN/GaN heterostructures offer the highest possible 2D electron gas concentration with reasonable mobility while the thinnest possible barrier in single heterostructure based HEMTs. As a result, they are very attractive for ultra-scaled high-speed GaN transistors (ft/fmax > 200 GHz). Indeed our group was the first to demonstrate promising results of AlN/GaN HEMTs: Idmax of 2.3 A/mm, gm,ext of 480 S/mm and gm,int of > 1 S/mm, and extrinsic ft/fmax of 52/60 GHz. [Zimmermann 2008 IEEE EDL] However, it has been challenging to harvest these properties due to ohmic contact formation and gate leakage issues. In this program we focused on the following tasks based on our early results: A. Improvement of the AlN/GaN heterostructure grown by MBE to achieve Rsh < 160 ohm/sq. B. Growth and fabrication of AlN/GaN/AlGaN back barrier HEMTs. C. Improvement of ohmic contacts and gate dielectrics to achieve Id,max of 2.5 A/mm and gm of 600 mS/mm. The research findings have been documented in two Ph.D. dissertations [Yu Cao 2010 and David Deen 2011] and six journal publications.

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Final Technical Report on

Ultrascaled AlN/GaN HEMT Technology for mm-wave RF applications

(N00014-08-1-1184)

July 23, 2008 to July 31, 2010

By Huili (Grace) Xing and Debdeep Jena

Electrical Engineering Department, University of Notre Dame

Phone: (574)631-9108, Fax: (574)631-4393, Email: hxing@nd.edu

Phone: (574)631-8835, Fax: (574)631-4393, Email: djena@nd.cdu

To: Paul Maki

Electronics, Sensors and Network Research (Code 312)

Office of Naval Research

875 N. Randolph Street

Arlington, VA 22203-1995

Phone: (703)696-3060

Email: Paul.maki@navy.mil

Project overview: AlN/GaN heterostructures offer the highest possible 2D electron gas concentration with reasonable mobility while the thinnest possible barrier in single heterostructure based HEMTs. As a result, they are very attractive for ultra-scaled high-speed GaN transistors (f_t/f_{max} > 200 GHz). Indeed our group was the first to demonstrate promising results of AlN/GaN HEMTs: I_{dmax} of 2.3 A/mm, $g_{m,ext}$ of 480 S/mm and $g_{m,int}$ of > 1 S/mm, and extrinsic f_t/f_{max} of 52/60 GHz. [Zimmermann 2008 IEEE EDL] However, it has been challenging to harvest these properties due to ohmic contact formation and gate leakage issues. In this program we focused on the following tasks based on our early results:

A. Improvement of the AlN/GaN heterostructure grown by MBE to achieve R_{sh} < 160 ohm/sq.
B. Growth and fabrication of AlN/GaN/AlGaN back barrier HEMTs.
C. Improvement of ohmic contacts and gate dielectrics to achieve $I_{d,max}$ of 2.5 A/mm and g_m of 600 mS/mm.

The research findings have been documented in two Ph.D. dissertations [Yu Cao 2010 and David Deen 2011] and six journal publications. Some of the key findings are summarized below.

A) Improvement of AlN/GaN heterostructures to achieve R_{sh} < 160 ohm/sq.

Our previous studies showed that the 2DEG mobility in the AlN/GaN heterostructure is limited by interface roughness scattering. With a perfect interface, the 2DEG mobility is supposed to ~ 2,000 cm^2/Vs at RT and ~ 10,000 cm^2/Vs for $n_s > 1.5x10^{13}$ cm^{-2}. Therefore, extensive growth studies have been carried out to improve the interface roughness. Shown below are several figures taken from Yu Cao's Ph.D. dissertation to highlight a few experimental results. In the first set of experiment the 2DEG mobility improved by ~ 25% by increasing the growth rate from 86 nm/hr to 210 nm/hr; in the second set of experiment the 2DEG mobility further improved by ~ 20% by optimizing the Ga and Al fluxes during growth. In the optimized structures the best observed mobility is 1,860 cm^2/Vs at RT and 7,800 cm^2/Vs at 77 K for n_s = $2x10^{13}$ cm^{-2}. **The best achieved sheet resistance is 128 ohm/sq. at RT and 40 ohm/sq. at 77 K.** Shown in Figure 2.7 and 2.8 are the RT sheet resistance versus Ga flux and Al flux used during the MBE growth and the corresponding 2DEG mobility at RT and 77K.

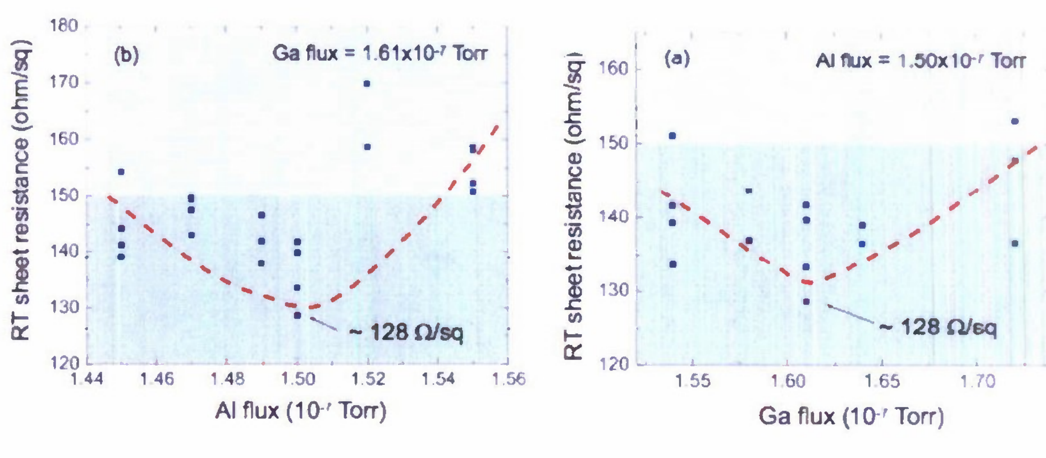


Figure 2.7. Effect of metal flux on the 2DEG mobility: (a) the Ga flux is optimized at $1.61x10^{-7}$ Torr and (b) the Al flux is optimized at $1.50x10^{-7}$ Torr. The dashed lines are guides to the eye.

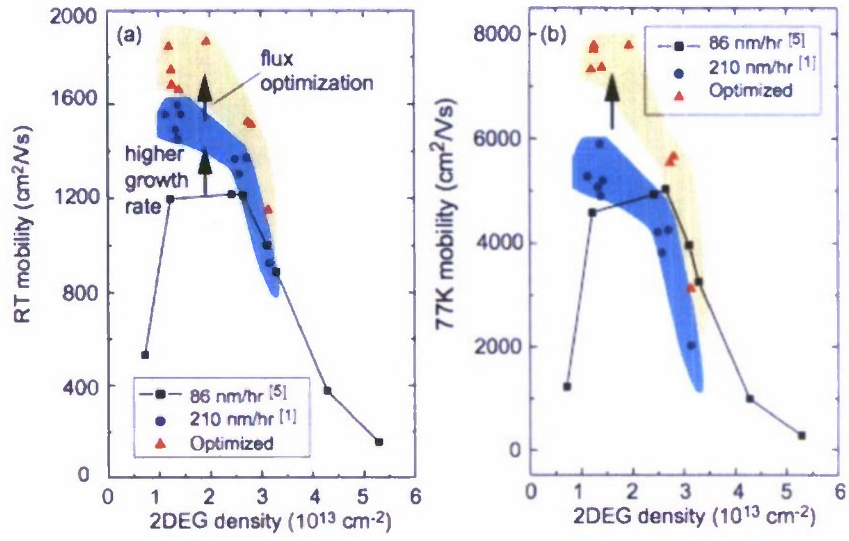


Figure 2.8. Mobility of 2DEGs measured at (a) room temperature and (b) 77 K for samples grown at 275 W (blue) and 150 W (red). The dashed lines are guides to the eye.

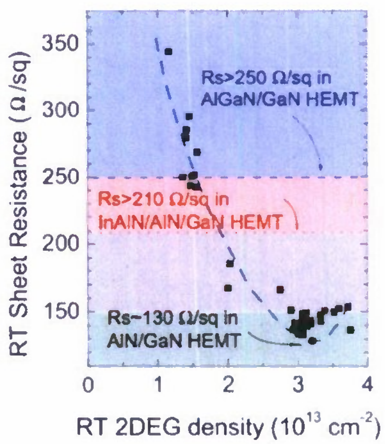


Figure 2.9. Plot of RT sheet resistance against 2DEG densities. The blue and red zones indicate the RT sheet resistance achieved in AlGaN/GaN and InAlN/AlN/GaN heterojunctions so far.

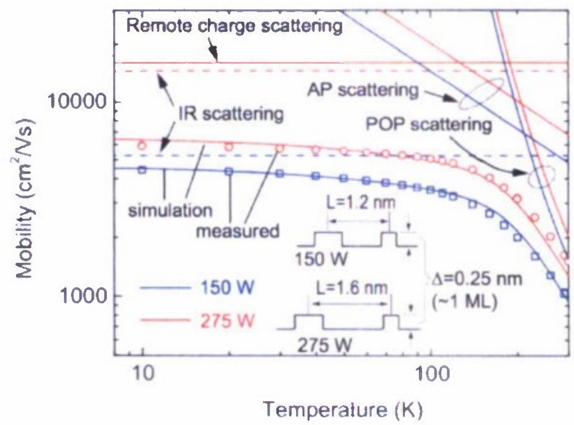


Figure 2.10. Measured temperature-dependent Hall-effect 2DEG mobility and calculations of various scattering mechanisms, with a fit to the measured data for two structures. The inset shows the fitted IR model indicating that the sample grown at at a higher growth rate has a larger correlation length at the AlN/GaN interface, or a smoother interface.

Also shown (Figure 2.9 and 2.10) are the experimentally achieved RT sheet resistance versus 2DEG concentration in single junction AlN/GaN heterostructures and the modeling of temperature-dependent mobilities in comparison to the experimental data. It was found that indeed the interface roughness (IR) scattering reduced in AlN/GaN grown at a higher growth rate. The extraordinarily large 2DEG concentration also presented another interesting opportunity for us to experimentally measure in AlN/GaN heterostructures how many sub-bands are occupied by electrons and the energy separation between the occupied sub-bands [Cao APL 2008]. Shown in Figure 2.11 and 2.12 are these results. The transverse magnetoresistance R_{xx} versus 1/B clearly showed two periods: the small period corresponds to the first sub-band electrons (1.18×10^{13} cm^{-2}) and the large period corresponds to the second sub-band electrons (0.0605×10^{13} cm^{-2}). It was found in this particular structure (2.3-nm-AlN/GaN), the first sub-

band is located 141.4 meV below the Fermi level and the second sub-band is located 7.2 meV below the Fermi level.

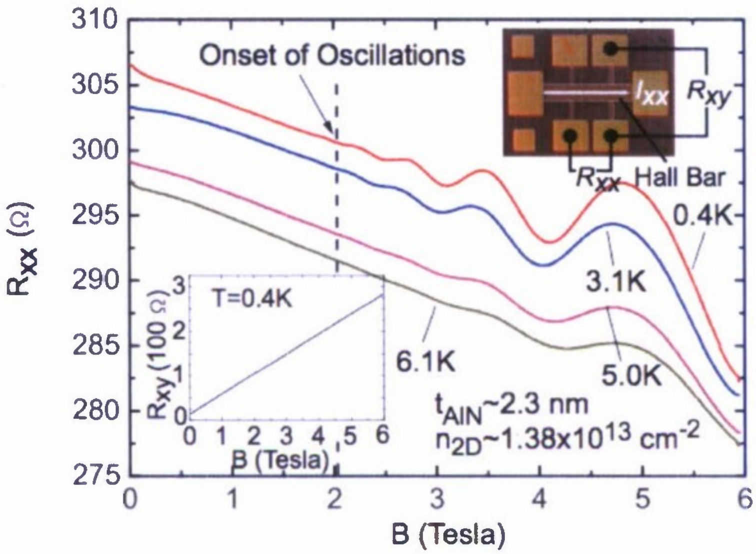


Figure 2.11. Measured transverse magnetoresistance R_{xx} vs B for different temperatures; the insets show measured R_{xy} vs B and the Hall bar used for the measurements.

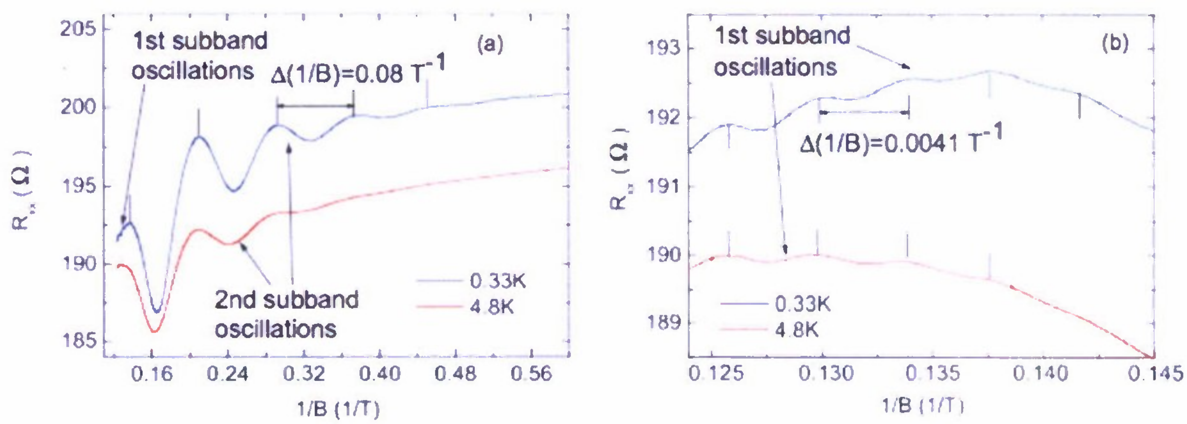


Figure 2.12. Measured transverse magnetoresistance R_{xx} is plotted against 1/B for the temperatures of 0.3 K and 4.8 K. The period of 1st subband oscillations is 0.0041 T^{-1} and that of 2nm subband is 0.08 T^{-1}.

B) Growth and fabrication of AlN/GaN/AlGaN back barrier HEMTs and polarization engineered buffer leakage removal

In our early demonstrations the AlN/GaN HEMTs suffered severe buffer leakage thus it was difficult to pinch off devices with a gate length shorter than 200 nm. To curb the parallel conduction problem in the buffer that is normally about 200 nm thick regrown on top of SI-GaN

templates, we investigated two strategies. The first strategy is to insert a thin layer of AlN (~ 1 nm) grown under nitrogen rich condition as the first nucleation step in the HEMT structure growth by MBE [Cao APL 2010]. Due to the polarization charges at AlN/GaN interface, an effective back barrier is created since the bands at the regrowth interface was raised up close to the valence band edge, as shown in Figure 4.8 from Yu Cao's Ph.D dissertation. The origin of the undesired conducting channel is the incorporation of impurities, including Si, O, C and etc, at the regrowth interface, as confirmed by the SIMS study. The structural quality of the AlN nucleation layer was characterized by XRD and TEM. Shown in Figure 4.18 and 4.19, The AlN nucleation layer appears to be uniform with low roughness, confirmed by the interference fringes of X-ray beams bouncing back and forth between the top AlN and the bottom AlN nucleation layer. The removal of the buffer leakage is demonstrated by both the C-V and I-V measurements, shown in Figure 4. 21 and 4.22. With the polarization-engineered buffer, no accumulated charges were observed at the regrowth interface and the HEMT also showed improved Ion/Ioff ratio (from 3 improved to over 7 orders of magnitude) with the gate leakage current being the limiting factor.

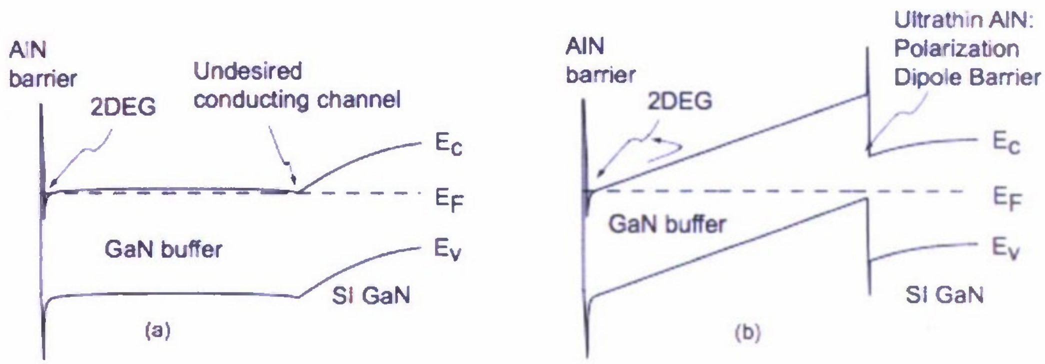


Figure 4.8. Band diagrams for (a) AlN HEMT without AlN NL and (b) AlN HEMT with 1.5 nm AlN NL.

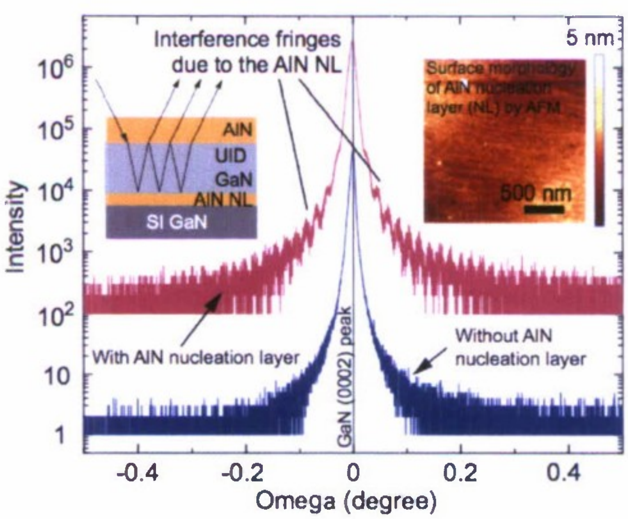


Figure 4.18. X-ray measurement results, showing cavity resonance fringes caused by the AlN NL, and its absence in the control sample. The insert shows a 2μm×2μm AFM scan with the smooth surface of the AlN nucleation layer.

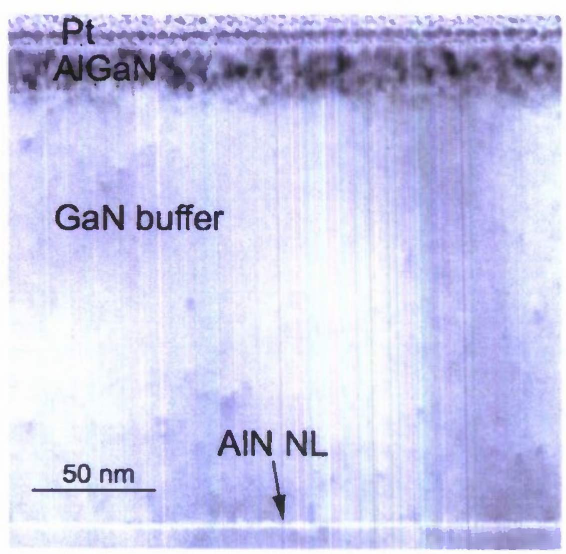


Figure 4.19. TEM image shows the AlN NL uniformly covers the GaN template at the regrowth interface. (Image provided by Prof Tom Kosel and Jai Verma)

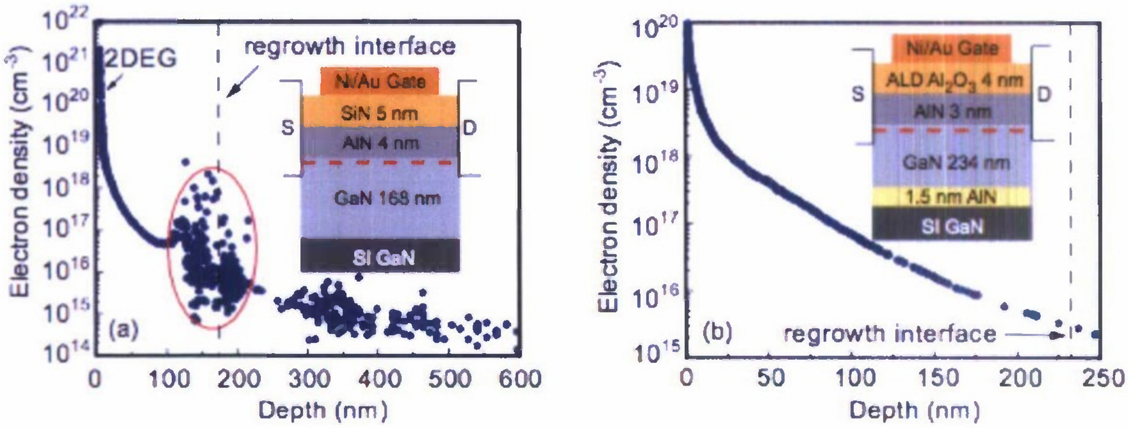


Figure 4.21. Comparison of buffer leakage in the control sample (blue), with 60 sec N_2 plasma treatment (green), and with 1.5 nm AlN nucleation layer (red).

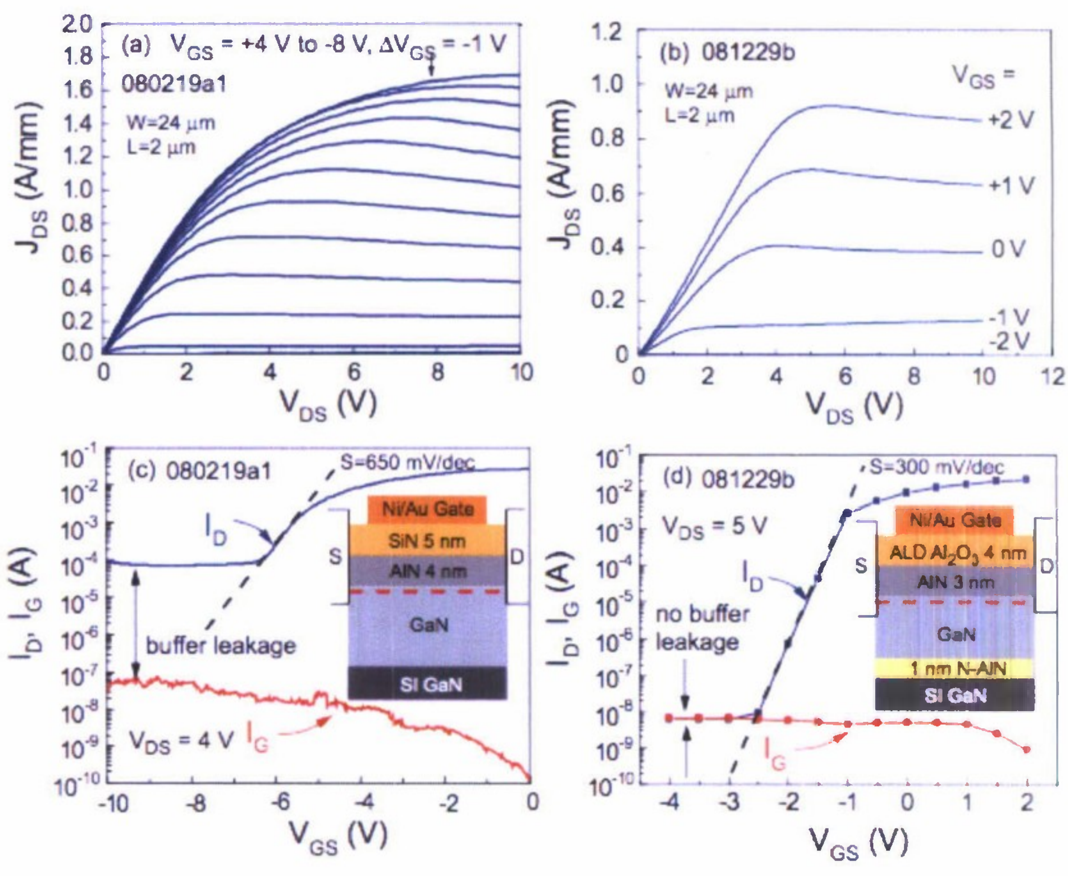
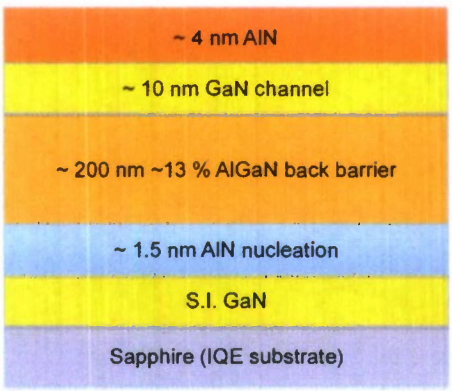
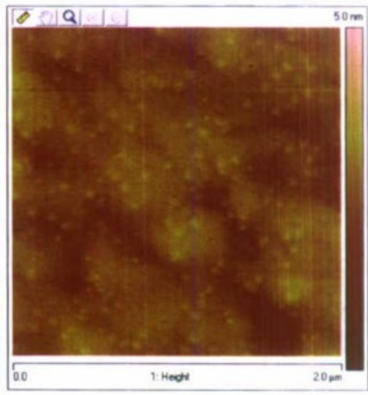
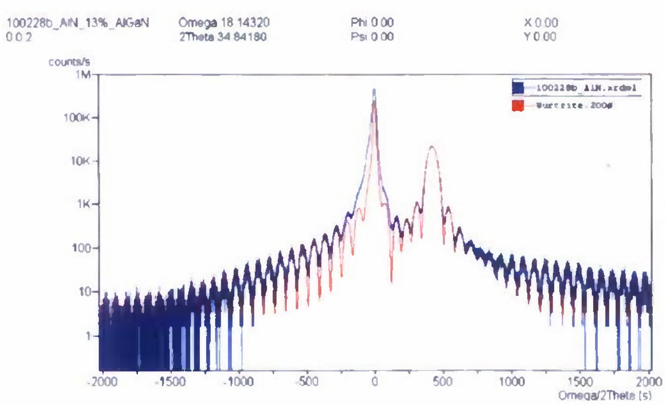


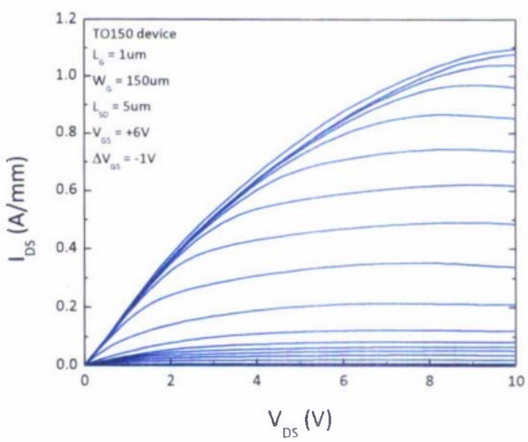
Figure 4.22. The transfer characteristics show that (a) the control sample suffers from severe buffer leakage, and (b) in the sample with the AlN NL the buffer leakage has been decreased lower than the gate leakage.

The second strategy is to incorporate AlGaN back barriers. Several AlN/GaN and high Al composition AlGaN/GaN heterostructures were grown with AlGaN back barriers with the Al composition as high as 13%. Unfortunately the cleanroom at UND moved to the new Engineering building taking about one year from 2009 to 2010, thus the samples could not be processed at UND. These devices were sent to David Deen, who is Xing's Ph.D. student and was working in Steve Binari's group at NRL. There are several interesting observations made by David Deen by comparing the AlN/GaN heterostructures grown at UND and at NRL: the dry etch rate of AlN grown at UND is much slower than that grown at NRL, and the ohmic contacts were more difficult to make on UND AlN/GaN heterostructures than those grown at NRL. The underlying reasons are still unclear to us. There was one hypothesis that the UND AlN may be partly Al_2O_3. However, it were true, we could have expected lower 2DEG concentration and mobility in UND AlN/GaN heterostructures; the fact is that the UND AlN/GaN heterostructures offer the highest 2DEG concentration with the highest mobility in the literature. Shown below is one of the samples with AlGaN back barrier. The AFM and XRD results indicate the good structural quality. The Hall measurement showed 1090 cm^2/Vs and 2.2×10^{13} cm^{-2} in the channel, which is very decent for a backbarrier HEMT structure with a 10 nm GaN channel. Long gate HEMTs showed reasonable drain output current density, but the devices suffered severely from the poor ohmic contacts.



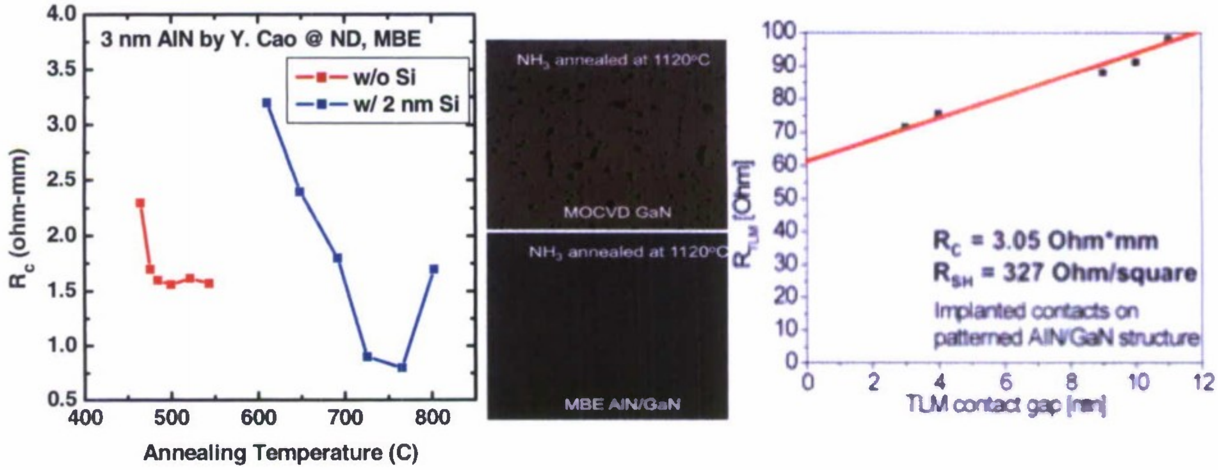






C) Improvement of ohmic contacts and gate dielectrics

AlN, being the largest bandgap semiconductor investigated to date, is not easy to make ohmic contacts to. Our earlier studies showed that the higher the 2DEG mobility the more difficult it is to make ohmic contacts to AlN/GaN heterostructures. Toward this end, we investigated several techniques: 1) insertion of Si interlayer in the ohmic metal stack, 2) ion implantation, 3) recessed ohmic etch prior to ohmic metallization, and 4) regrowth of the source and drain regions.



Figures showing ohmic contacts made with (left) Si interface and (right) Si ion implantation.

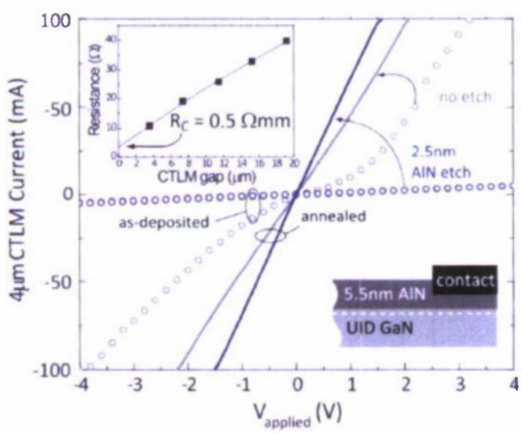


Fig. 1. Two-point current-voltage characteristics comparing the 2.5 nm pre-metallization etched and non-etched contacts to AlN/GaN for as-deposited and post-annealed metal. IV characteristics demonstrate the reduction in contact resistance due to the pre-metallization etch. Inset showing CTLM measurement and fit data for the lowest R_c value of 0.5 Ω mm obtained through the pre-metallization etch.

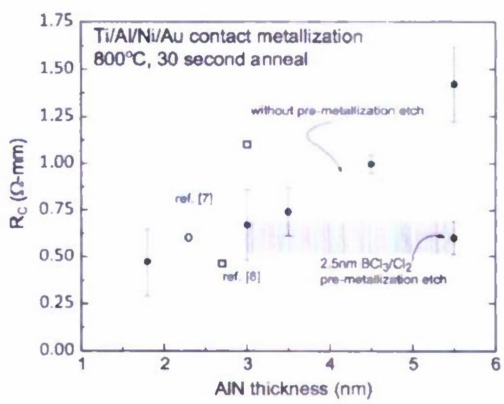


Fig. 3. Contact resistance comparison as a function of AlN barrier thickness. Closed circles represent our contact resistances to AlN/GaN heterostructures *without* the pre-metallization etch demonstrating an increasing R_c with increased AlN thickness (error bars denote one standard deviation from the mean). Contact resistances to AlN/GaN heterostructures *including* the 2.5 nm pre-metallization etch is plotted with its range in standard deviation in grey showing the significant reduction in resistance. Open squares represent contact resistances taken from the corresponding references.

Figures from David A. Deen, David F. Storm, D.S. Katzer, David J. Meyer, Steve C. Binari. "Dependence of ohmic contact resistance on barrier thickness of AlN/GaN HEMT structures." Solid State Electronics 54, 613 (2010).

Shown above are the major results from these efforts. The Si-interlayer in the ohmic metal stack showed a promising trend: the resultant contact resistance being smaller but with a higher annealing temperature. The AlN/GaN heterostructure after ion activation annealing at 1120 °C showed a smooth morphology under optical microscope in comparison to ion-implanted GaN. This is remarkable since the AlN barrier is only 3.5 nm thick. However, the contact resistance was still high. The more promising approach was the shallow recess etch prior to the ohmic metallization developed by David Deen using the AlN/GaN heterostructures grown at NRL. In this work he successfully lowered the contact resistance from over 1 ohm-mm to 0.5 ohm-mm. However, this technique has not been successfully applied to the UND AlN/GaN heterostructures yet. More recently we investigated ohmic regrowth by MBE for InAlN/AlN/GaN HEMTs and a regrowth-2DEG interface contact resistance of 0.05 ohm-mm has been achieved. We plan to adopt the regrown contacts for AlN/GaN HEMTs in the near future.

Another pressing issue for ultrathin barrier HEMTs is high quality gate dielectrics. In our earlier demonstration, an e-beam evaporated Al_2O_3 gate insulator was used [Zimmermann EDL 2008, Deen PSS 2008]. PECVD SiN deposited at Triquint Semiconductors was also explored as a gate dielectric, showing lower gate leakage in comparison to e-beam evaporated Al2O3 [Zimmermann LEC 2009]. An atomic layer deposition (ALD) tool (Savannah 100 from Cambridge Nanotechnology) was purchased and installed under another grant. Al_2O_3 deposited by thermal ALD has been routinely used in our HEMT fabrication processes including several runs at NRL as well. David Deen also investigated several ALD high K dielectrics deposited at NRL and U. of Maryland, including Al_2O_3, HfO_2 and Ta_2O_5. The results are detailed in his Ph.D. dissertation. Though it was not included in his dissertation, David also discovered that the ALD Al_2O_3 deposited at UND is of higher quality since it can stand a large voltage swing and exhibits lower gate leakage currents. However, more detailed studies are necessary especially for ultra-thin barrier III-N semiconductor heterostructures since their properties are subject to strong polarization effects and dominated by the surface states in the un-doped structures.

To achieve the original goal of 2.5 A/mm drain output current density and 600 mS/mm transconductance, it is necessary to lower the contact resistance to be < 0.3 ohm-mm, device on-resistance to be < 1 ohm-mm. Though this was not achieved in the duration of this grant, it is worth noting that under the recent DARPA NEXT program $I_{d,max}$ > 2 A/mm and g_m > 600 mS/mm have been routinely achieved by various performers including our research group.

<u>**Personnel supported**</u>: 1.5 graduate students and 0.5 postdoctoral researcher

<u>**Equipment purchased:**</u> none

<u>**Publications/Presentations:**</u>

[1] Yu Cao, Ph.D. Dissertation: Study of AlN/GaN HEMTs: MBE growth, transport properties and device issues. Advisors: Debdeep Jena and Huili (Grace) Xing. University of Notre Dame, 2010.

[2] David Deen, Ph.D. Dissertation. Advanced designs of ultra-thin AlN/GaN HEMTs; A study of device design, modeling and analysis. Advisor: Huili (Grace) Xing. University of Notre Dame,

2011.

[3] Yu Cao, **Huili Xing**, and Debdeep Jena. *Polarization-mediated remote surface roughness scattering in ultrathin barrier GaN high-electron mobility transistors. Appl. Phys. Lett.*, **97**, 222116 (2010).

[4] *Yu Cao, Tom Zimmermann*, **Huili Grace Xing** and Debdeep Jena. *Polarization-engineered removal of buffer leakage for GaN HEMTs. Appl. Phys. Lett., 96(4), 042102 (2010).*

[5] *Tom Zimmermann, Yu Cao*, Paul Saunier, Debdeep Jena and **Huili Grace Xing**. *4-nm AlN barrier all binary HFET with SiNx gate dielectric.* International Journal of High Speed Electronics and Systems, **19**, 153 (2009).

[6] *Yu Cao*, Kejia Wang, Alexei Orlov, **Huili Xing** and Debdeep Jena. *Very low sheet resistance and Shubnikov-de-Haas oscillations in two dimensional electron gases at ultrathin binary AlN/GaN heterojunctions.* Appl. Phys. Lett., 92(15), 152112, (2008).

[7] *David Deen, Tom Zimmermann, Yu Cao*, Debdeep Jena and **Huili Xing**. *2.3nm barrier AlN/GaN HEMTs with insulated gates.* Physica Status Solidi (c), 5(6), 2047 (2008).

[8] *Tom Zimmermann, David Deen, Yu Cao, John Simon*, Patrick Fay, Debdeep Jena and **Huili Xing**. *AlN/GaN insulated gate HEMTs with 2.3 A/mm output current and 480 mS/mm transconductance.* IEEE Electron Device Lett., 29(7), 661, (2008).